EXPERIMENTAL CHARACTERIZATION OF AL – CU THERMAL CONTACT RESISTANCE BELOW 50 K

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- Measurement campaign
  - What do we want to do
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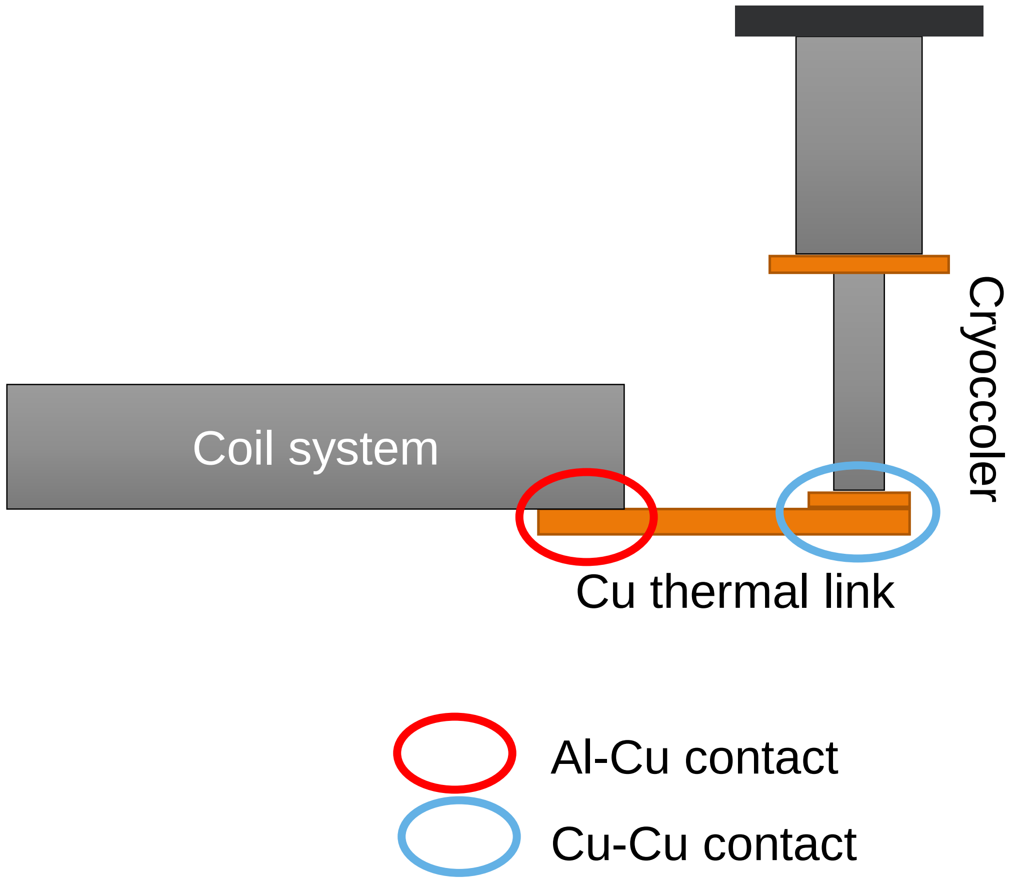
Motivation

- Measurements done in the framework of the project “IMDS*”
  - 3 conduction-cooled NbTi superconducting coils
  - For every 100 mK increase → 23% decrease in current
  - Thermal contact resistance (TCR) plays a big role!

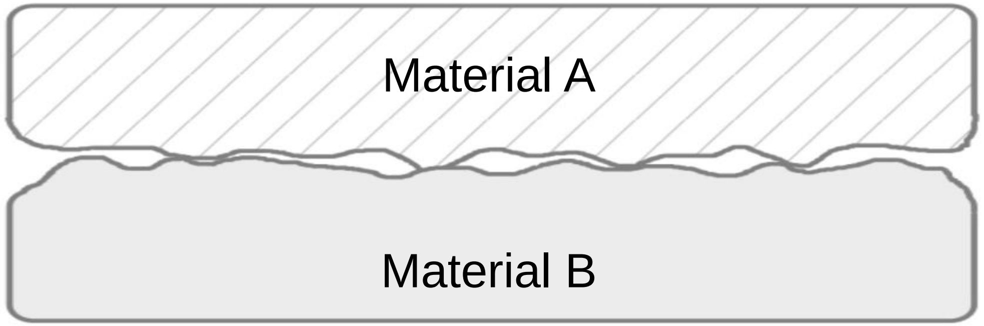


*URL: https://www.utwente.nl/en/tnw/ems/research/sust/MDS/

Literature on TCR of pressed metal contacts

Medium	Scales with	Best use
Dry	Force	
Grease	Area	Large areas Low pressure
Indium	Area	0.05-0.1 mm thick P > 1 MPa
Gold plated	Force	High force

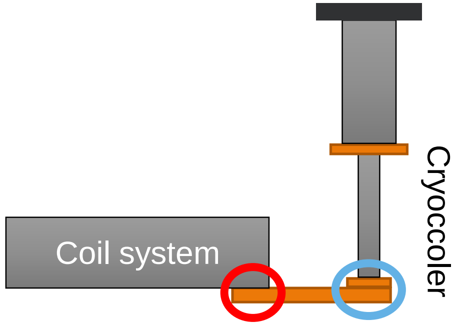
Jack W. Ekin, “*Experimental techniques for low-temperature measurements*”, 2016



- Temperature dependence: $TCR^{-1} = \alpha T^{\gamma}$
- For perfect surfaces @ T< 50 K:
  - γ =1 → electrons
  - γ = 3 → phonons
- Imperfect surfaces @ T< 50 K:
  - $1 < \gamma < 3$
  - γ decreases with α

E. Gmelin, et al. “Thermal boundary resistance of mechanical contacts between solids at sub-ambient temperatures”, J. Phys. D: Appl. Phys. 32, 1998

Measurement campaign



- Practical approach
  - Typical cold finger size area ≈ 35 cm^2 (≈ Ø68 mm cold finger)
  - 6 X M5 bolts – 5 N/m ≈ 2.7 tons force (calibrated at RT)

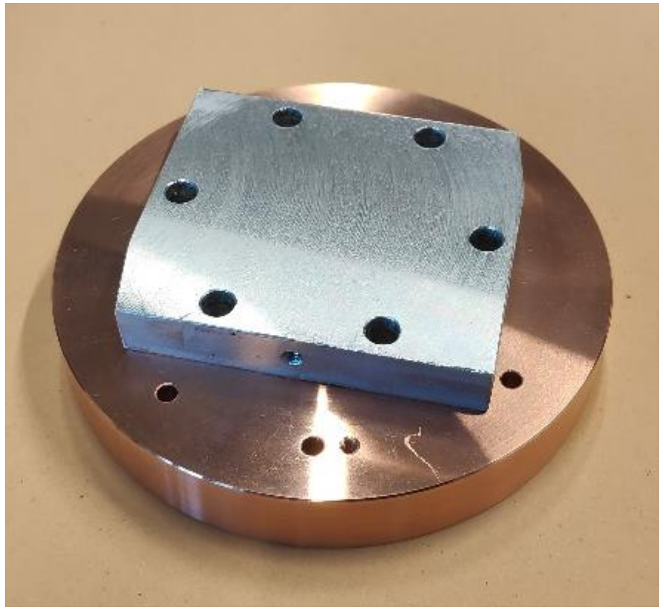
1. Al RRR 1600 – ETP Cu
2. ETP Cu – ETP Cu

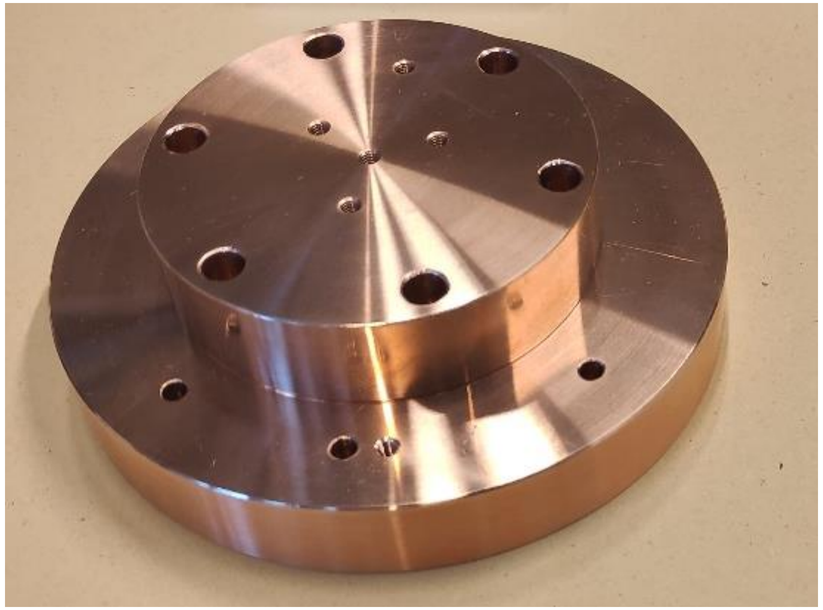
a) Dry
b) Apiezon-N
c) Indium foil
d) Apiezon-N loaded with Ag powder (5-8 μm)

Measurement campaign – Where are we now?

1) Al RRR 1600 – Cu RRR 50
   a) Dry
   b) Apiezon-N
   c) Indium foil
   d) Apiezon-N loaded with silver powder (5-8 μm)

2) Cu RRR50– Cu RRR50





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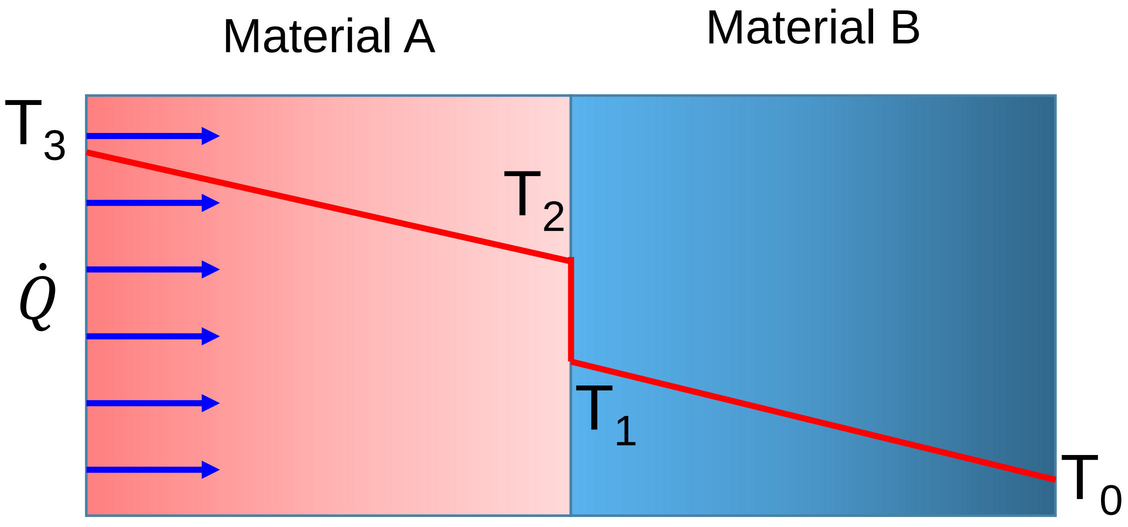
Thermal contact resistance – Steady state measurements

1) T_0 is fixed
2) Different loads $\dot{Q}$ are applied
3) Temperatures are stabilized
4) T_3 and T_0 are measured
5) $\frac{\partial(T_2 - T_1)}{\partial \dot{Q}}$, $_{\Delta T << T}$ ≈ TCR
6) For every temperature

   → 6 different $\dot{Q}$ are applied



$$TCR = \frac{T_2 - T_1}{\dot{Q}}$$

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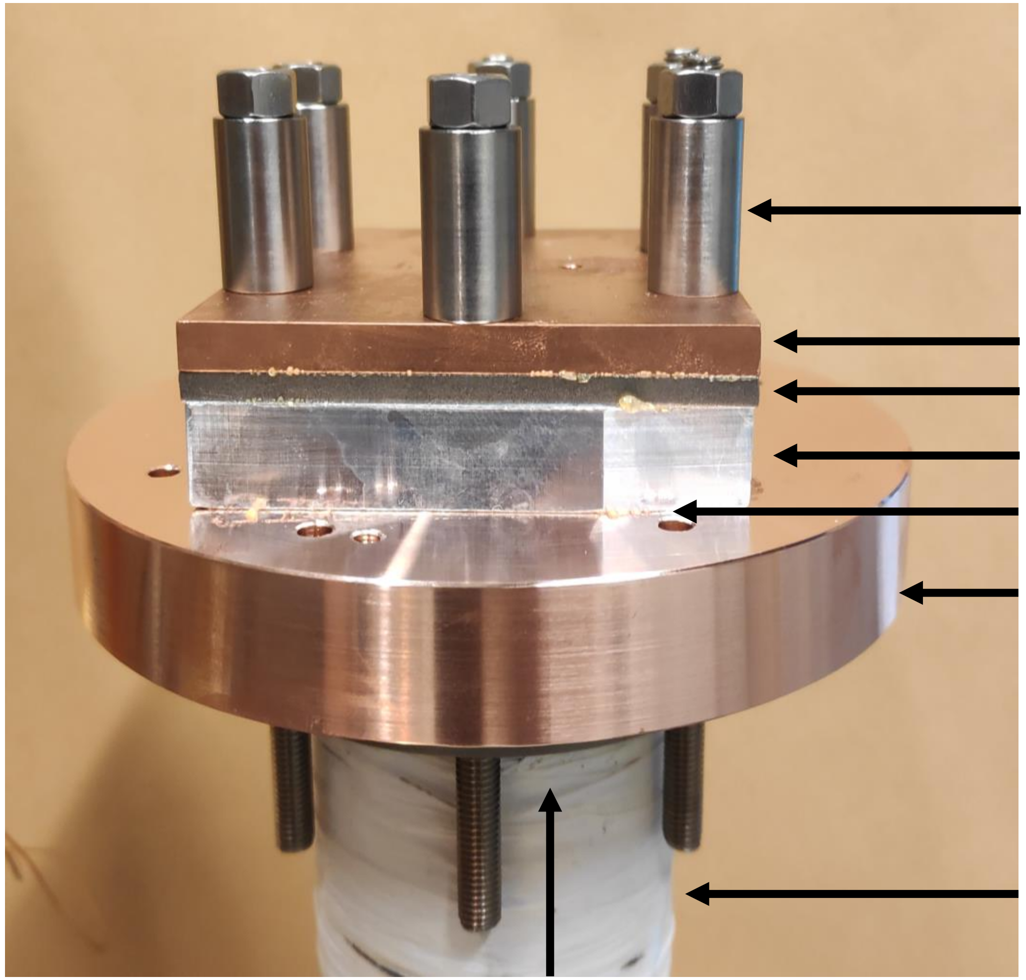
Set-up

- Manganine heater
  - Controls Cu temperature
- SS plate
  - Homogenizes pressure
- Cu plate
  - Homogenizes heat flux
- Ti bushings
  - Prevents differential thermal contractions



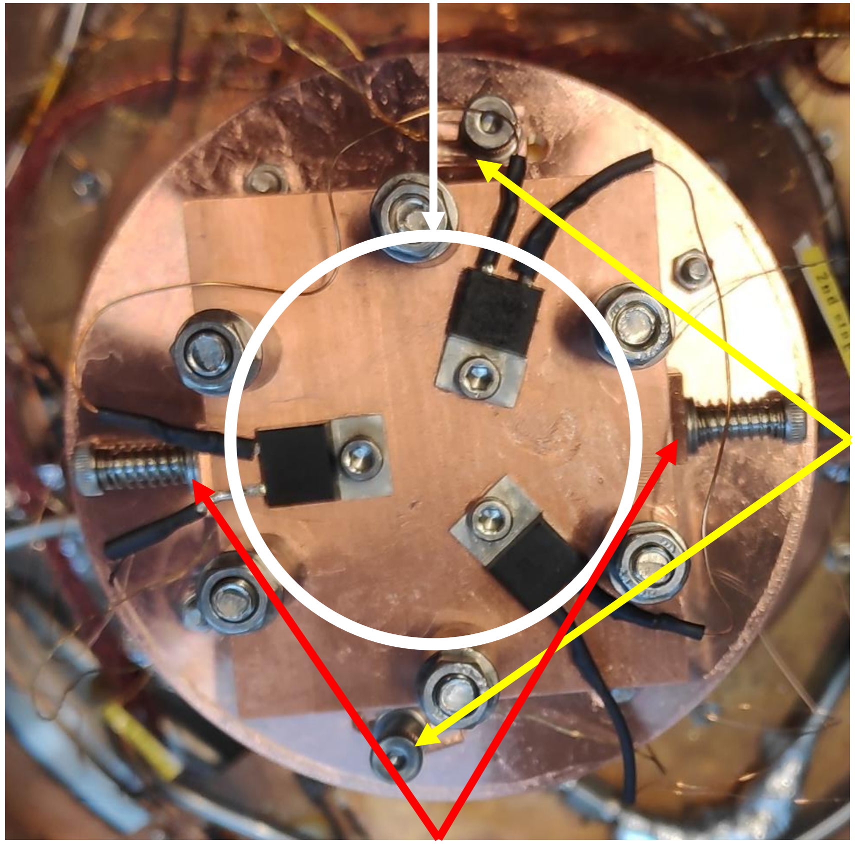
GM cooler →1 W @ 4.2 K

Set-up

- 250 Ω heater
  - Establishes a heat flux (max **10 W**)
  - **Heat leak** from

    2 X 0.2 mm Cu wires **< 1%**
- 4 calibrated Cernox® thermometers
  - 2 on the Al
  - 2 on the Cu

  Redundancy
- Thermal shield
  - Radiation < 1 mW



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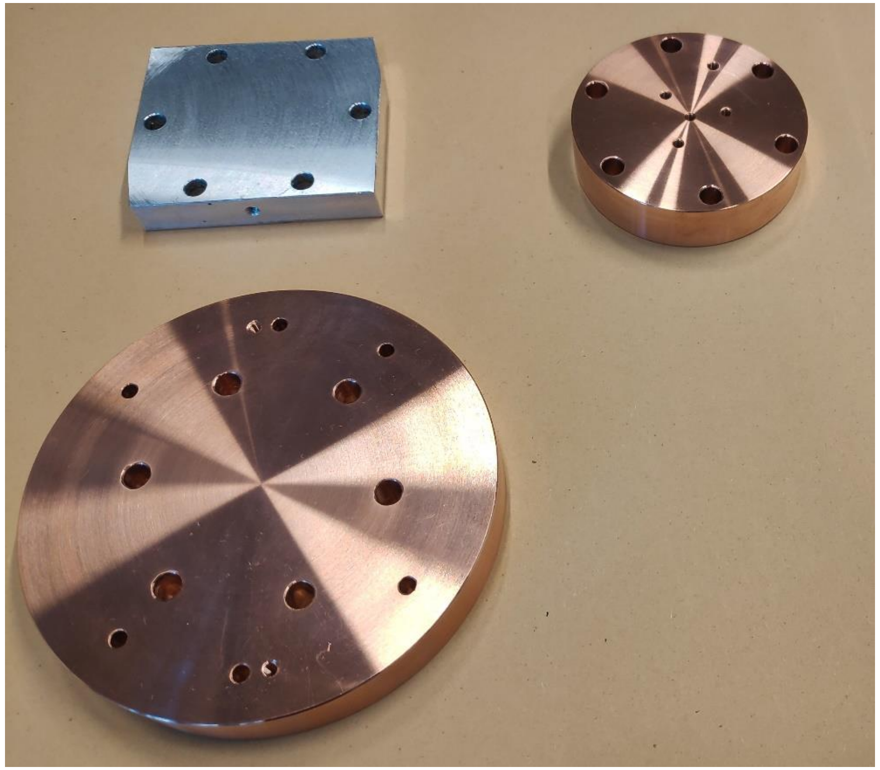
Measurement campaign – reproducibility

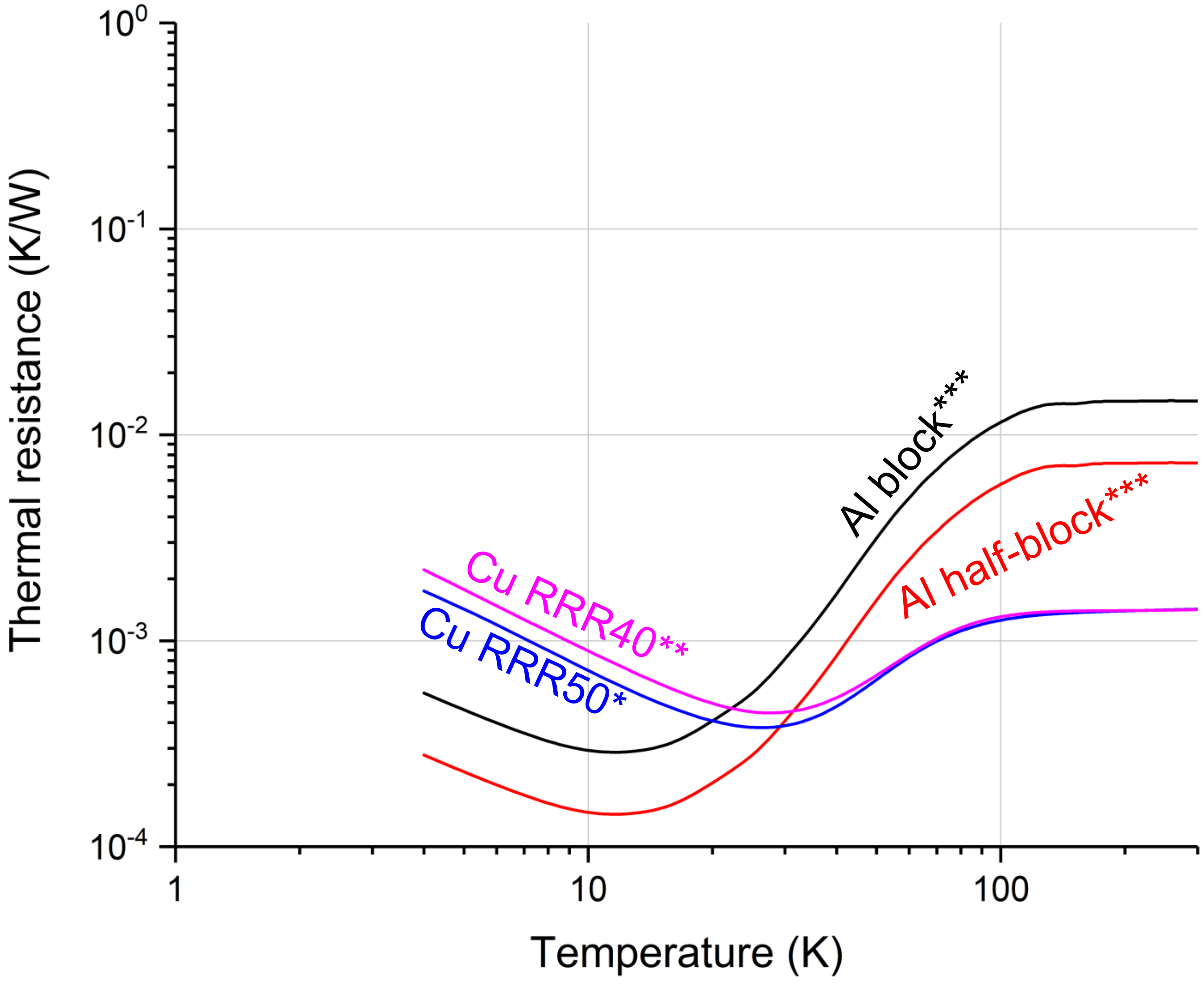
- For every measurement a new set of materials is used
- Every measurement is repeated twice (with new materials)
- The Cu and Al pieces are machined to < 1 μm average roughness
  - Will be verified by a surface profiler
- Cu is washed in acetic acid (99.7% purity) to remove oxide layer*

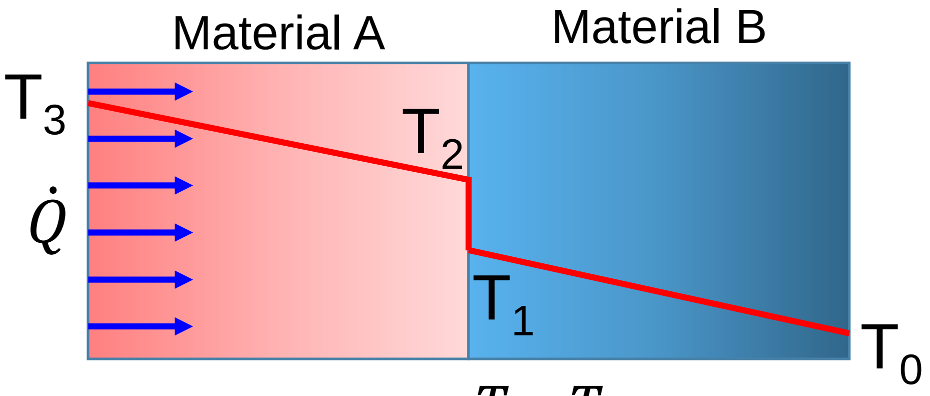


*K.L. Chavez, D. W. Hess, ''A Novel Method of Etching Copper Oxide Using Acetic Acid", *Journal of The Electrochemical Society*, 148, 2001

*NIST, (January, 2019), URL: https://trc.nist.gov/cryogenics/materials/materialproperties.htm
**J. G. Hust and A. B. Lankford, "Thermal conductivity of aluminium, copper, iron and tungsten from 1 K to the melting point", National Bureau of Standards, Boulder, Colorado, 1984. NBSIR 84-3007.
***Eckels Enginneering Inc., Cryodata Inc., Version 3.01

Results – Base line





$$\mathrm{TCR} = \frac{T_2 - T_1}{\dot{Q}}$$

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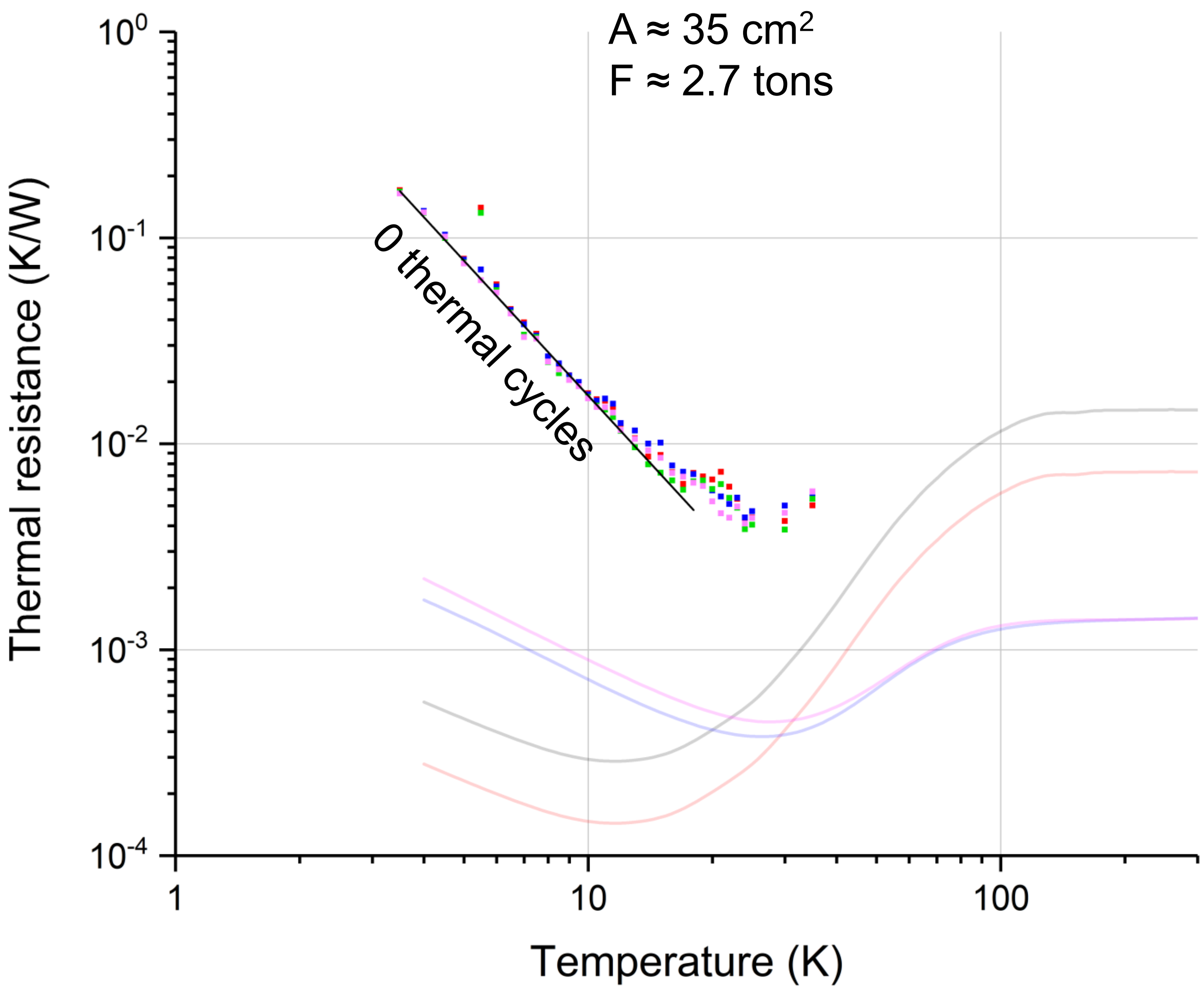
Results – Al – Cu dry contact



$$\mathrm{TCR}^{-1} = \alpha T^{\gamma}$$

Contact type	Thermal cycles	α	γ
Dry	0	0.39±0.02	2.18±0.04

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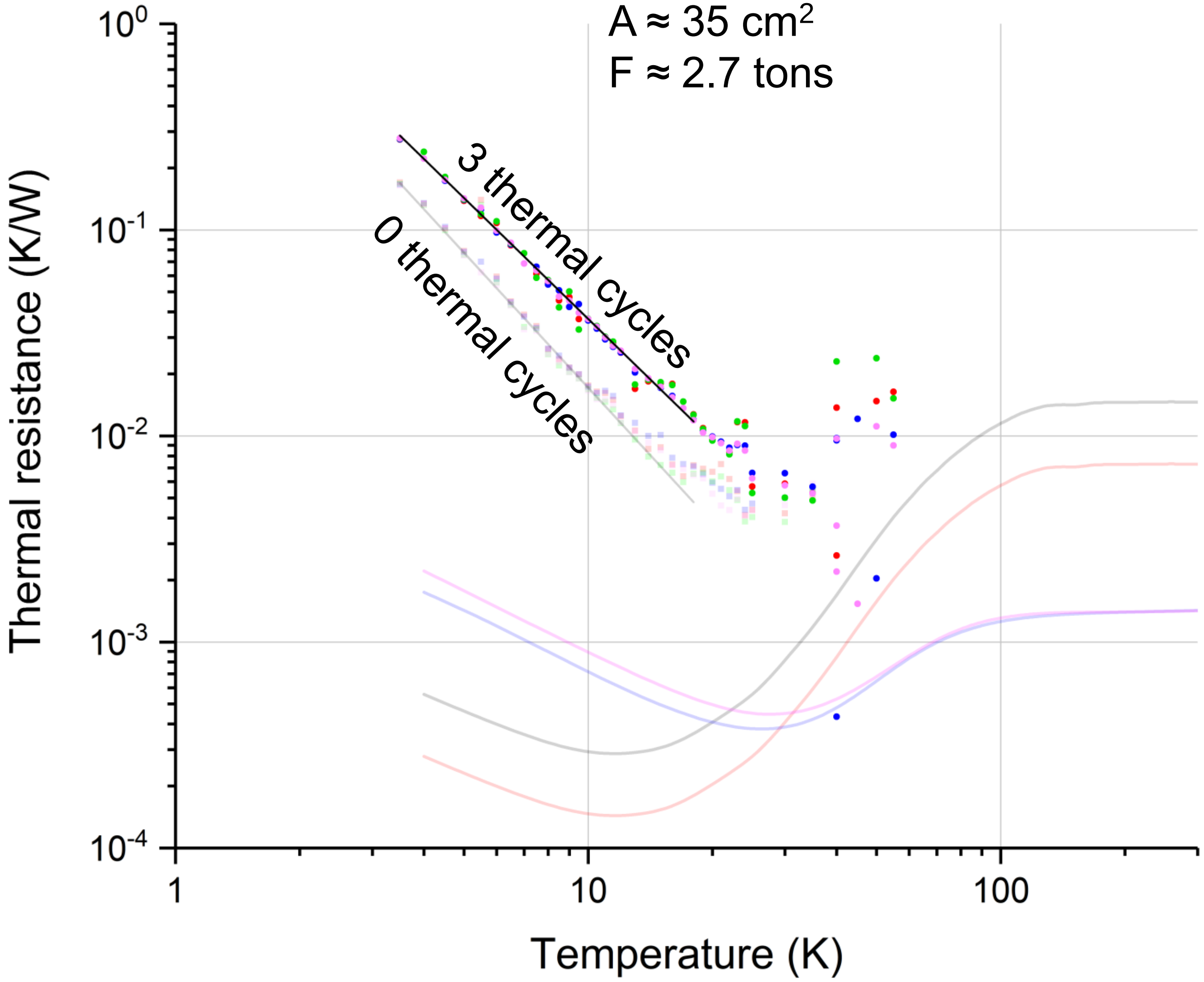
Results – Al – Cu dry contact after 3 thermal cycles with air contact



$$\mathrm{TCR}^{-1} = \alpha T^{\gamma}$$

Contact type	Thermal cycles	α	γ
Dry	0	0.39±0.02	2.18±0.04
Dry	3 with air	0.30±0.02	1.95±0.04

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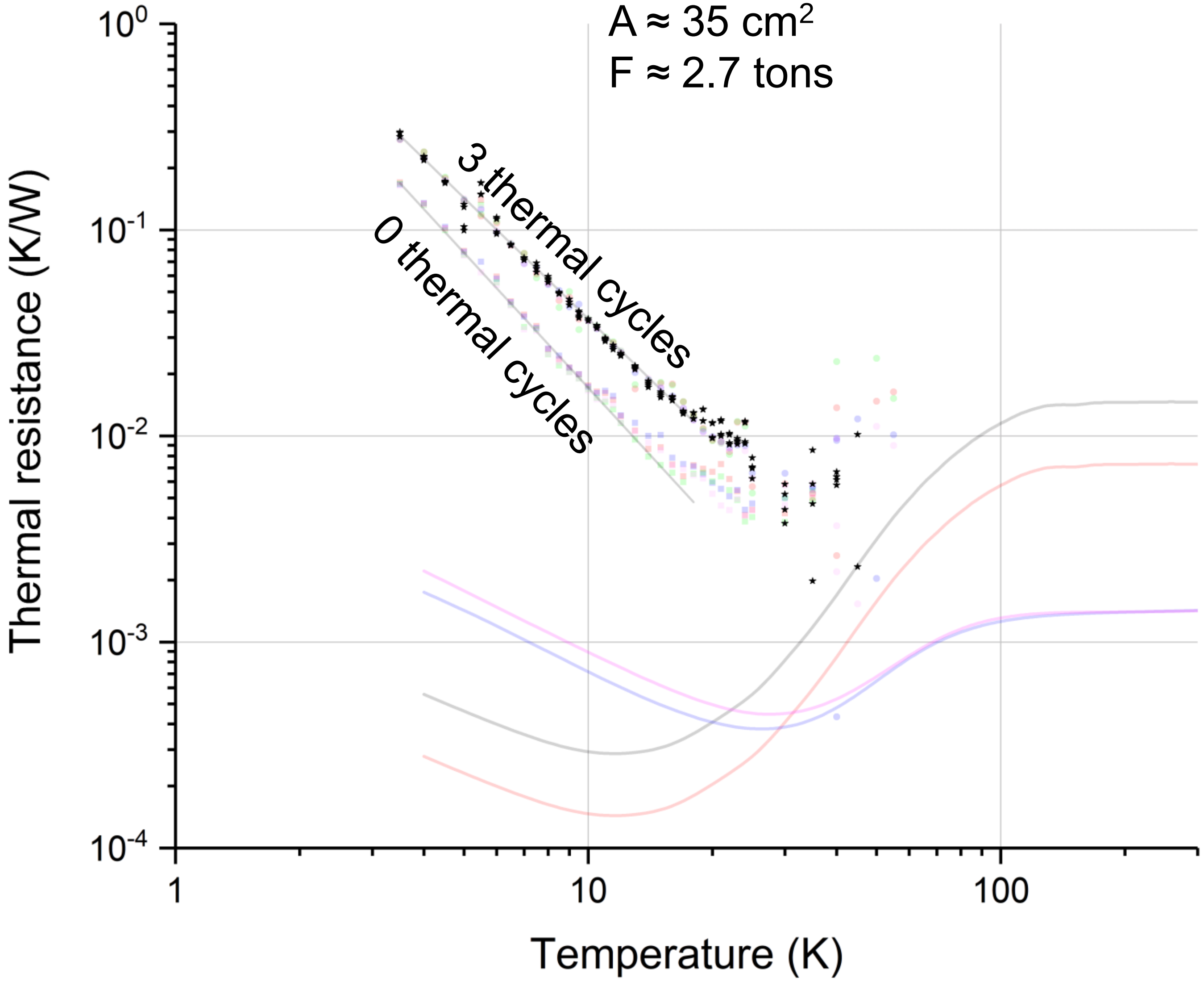
Results – Al – Cu dry contact repeated measurement



$$\mathrm{TCR}^{-1} = \alpha T^{\gamma}$$

Contact type	Thermal cycles	α	γ
Dry	0	0.39±0.02	2.18±0.04
Dry	3 with air	0.30±0.02	1.95±0.04

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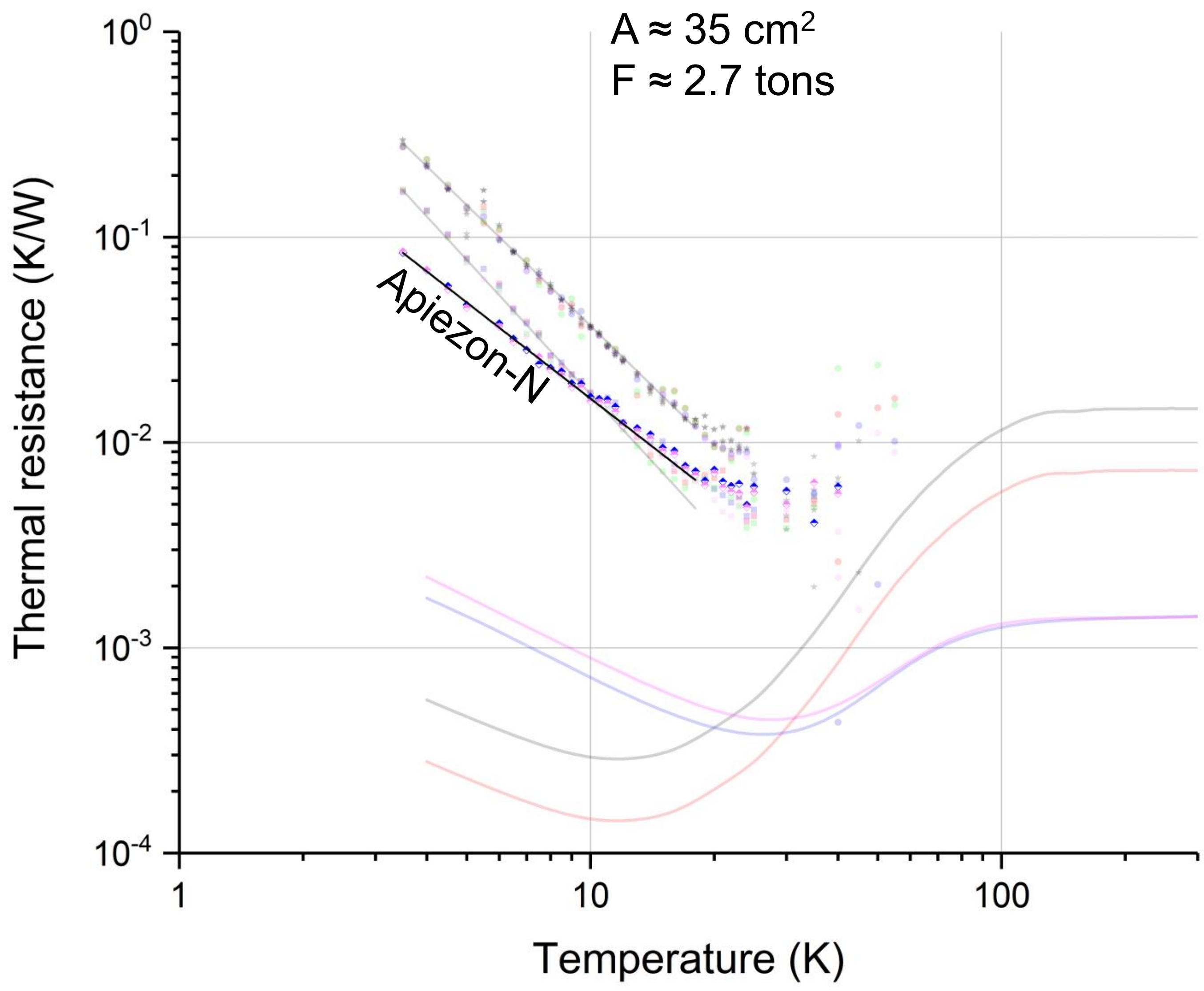
Results – Al – Cu apiezon-N



$$TCR^{-1} = \alpha T^{\gamma}$$

Contact type	Thermal cycles	α	γ
Dry	0	0.39±0.02	2.18±0.04
Dry	3 with air	0.30±0.02	1.95±0.04
Apiezon-N	0	1.7±0.2	1.55±0.02

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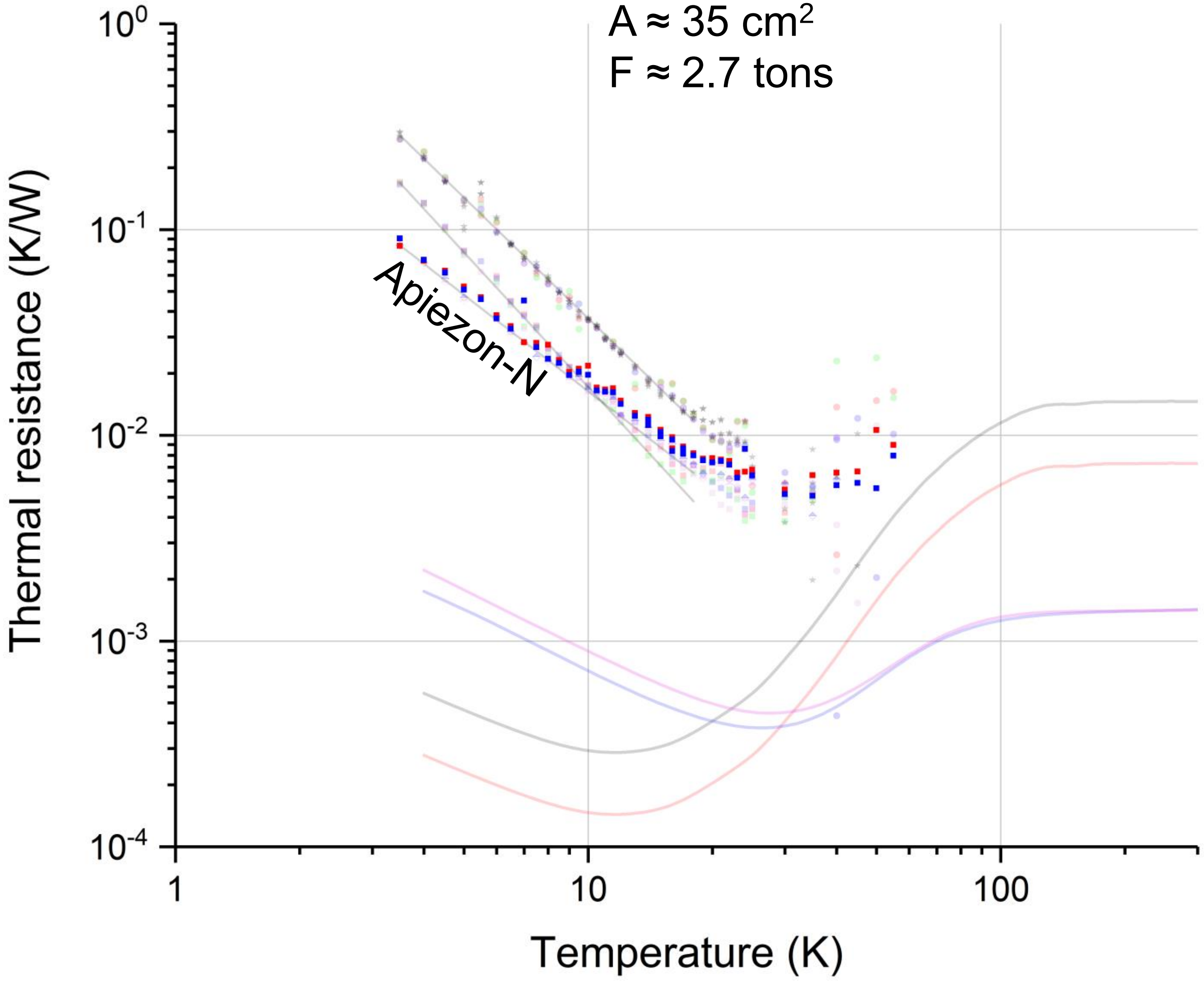
Results – Al – Cu apiezon after 1 thermal cycle



$$\mathrm{TCR}^{-1} = \alpha T^{\gamma}$$

Contact type	Thermal cycles	α	γ
Dry	0	0.39±0.02	2.18±0.04
Dry	3 with air	0.30±0.02	1.95±0.04
Apiezon-N	0	1.7±0.2	1.55±0.02
Apiezon-N	1	2.0±0.2	1.43±0.02

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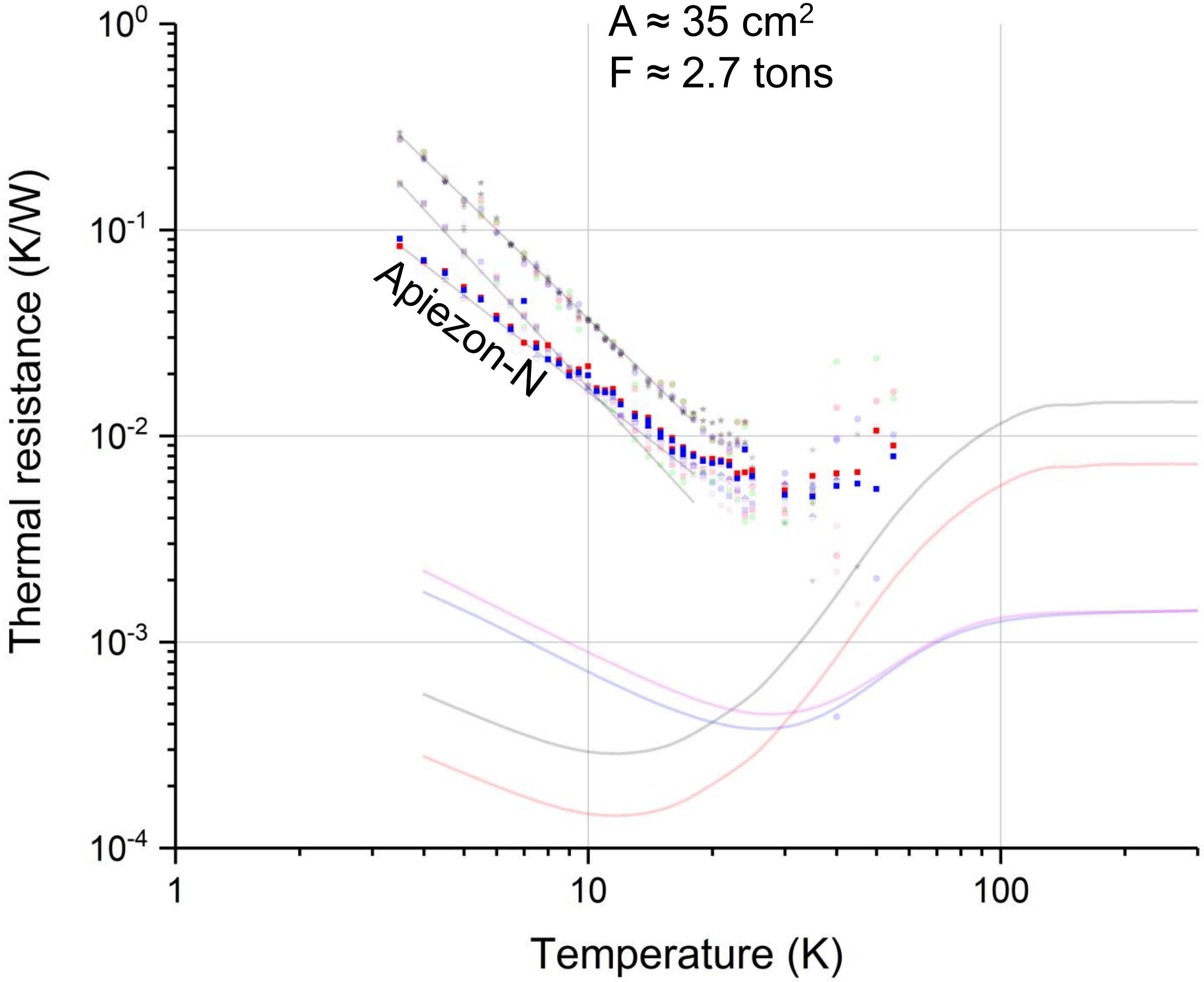
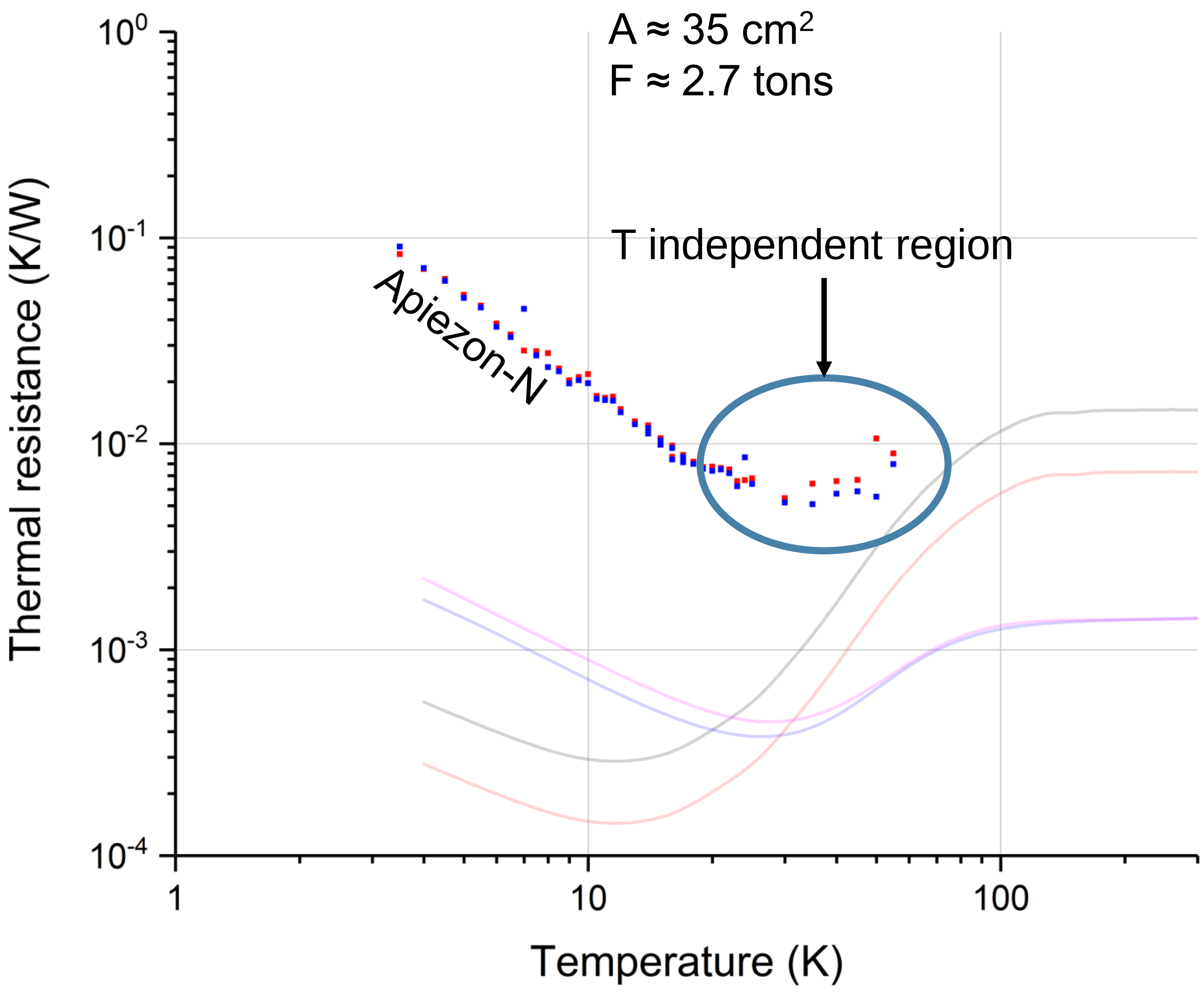
Results – Al – Cu apiezon after 1 thermal cycle



$$TCR^{-1} = \alpha T^{\gamma}$$

Contact type	Thermal cycles	α	γ
Dry	0	0.39±0.02	2.18±0.04
Dry	3 with air	0.30±0.02	1.95±0.04
Apiezon-N	0	1.7±0.2	1.55±0.02
Apiezon-N	1	2.0±0.2	1.43±0.02
Apiezon-N	1+1with air	1.7±0.2	1.54±0.02

Results – Al – Cu TCR @ intermediate temperature



- 20 – 50 K range measured accurately after heater upgrade (3 W → 10 W)

Conclusions

- TCR is crutial for conduction cooled SC coils design at Lhe temperatures
- The TCR between Cu RRR50 and Al RRR1600 was successfully measured
  - Dry contact
    - $\approx T^{-2}$ dependence was measured between 3.5 – 20 K
    - A degradation by a factor of 2 was observed after 3 thermal cycles and contact with air
  - Apiezon-N contact
    - $\approx T^{-1.5}$ dependence was measured between 3.5 – 20 K
    - No degradation was observed with 2 thermal cycles or air contact

Conclusions

- In the 20-60 K range, TCR seems to be temperature independent
- So far the lowest TCR at LHe temperature was obtained with Apiezon-N (≈70 mK/W)
- All these measurements will be done a second time to show reproducibility